Incorporating galaxy cluster triaxiality in stacked cluster weak lensing analyses

Zhuowen Zhang(1,3), Hao-yi Wu(2), Yuanyuan Zhang(3), Josh Frieman(1,3) et al.
1. Department of Astronomy & Astrophysics, University of Chicago, Chicago, IL
2. Physics Department, Boise State University, Boise, ID
3. Fermilab, Batavia, IL

DARK ENERGY SURVEY

ABSTRACT

Counts of galaxy clusters offer a high-precision probe of cosmology, but control of systematic errors will determine the accuracy, and thus the cosmological utility, of this measurement.

Using Buzzard simulations, we quantify one such systematic, the triaxiality distribution of clusters identified with the redMaPPer optical cluster finding algorithm, which was used in the Dark Energy Survey Year-1 (DES Y1) cluster cosmology analysis. **We also test the correlation of orientation with two other leading systematics in cluster cosmology---miscentering and projection---and find a null correlation**, indicating that triaxiality bias can be forward-modeled as an independent systematic.

The resulting mass bias confirms the DES Y1 finding that triaxiality is a leading source of bias in cluster cosmology. However, the richness-dependence of the bias confirms that triaxiality, along with other known systematics, does not fully resolve the tension at low-richness between DES Y1 cluster cosmology and other probes.

Our model can be used for quantifying the impact of triaxiality bias on cosmological constraints for upcoming weak lensing surveys of galaxy clusters.

BACKGROUND

Comprising a few to several hundred galaxies, galaxy clusters are tracers of the underlying dark matter structures. The mass of a galaxy cluster is difficult to directly observe. It is often inferred from another cluster observable through a mass-observable relation (MOR).

Optical surveys often deploy an observable called "richness" as a proxy for the galaxy count of clusters. In the redMaPPer cluster finder used by the Dark Energy Survey (DES), "richness" is defined by iteratively counting the number of galaxies in the clusters weighted by their probability of falling under the red-sequence.

In the weak lensing regime, the mass of ensemble averaged clusters for each richness bin is estimated by fitting the cluster lensing profile onto the best-fit analytical template. The precision of cluster cosmology study relies on an accurate statistical model relating these observables to cluster mass.

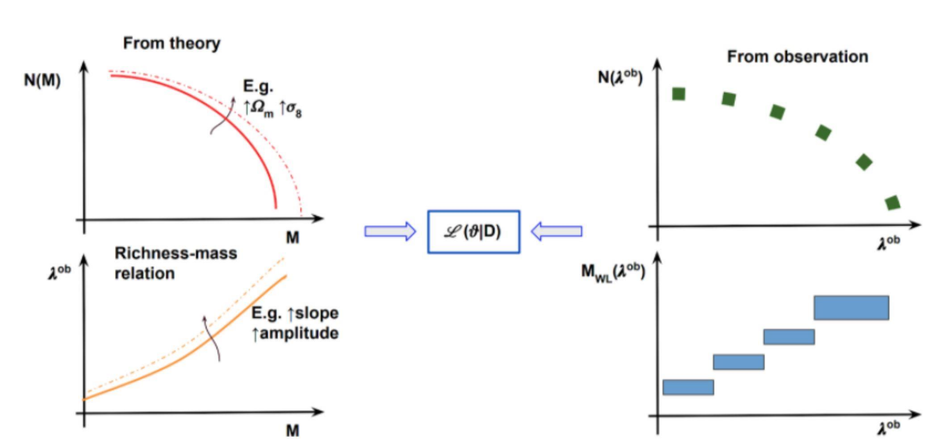


Figure 1: Observations simultaneously constrain the cluster number count and the richness-mass relation. By matching the theoretical predictions to best fit the observations we are able to infer cosmological parameters as Ω_m and σ_8. Image taken from DES Penn 2019 Conference.

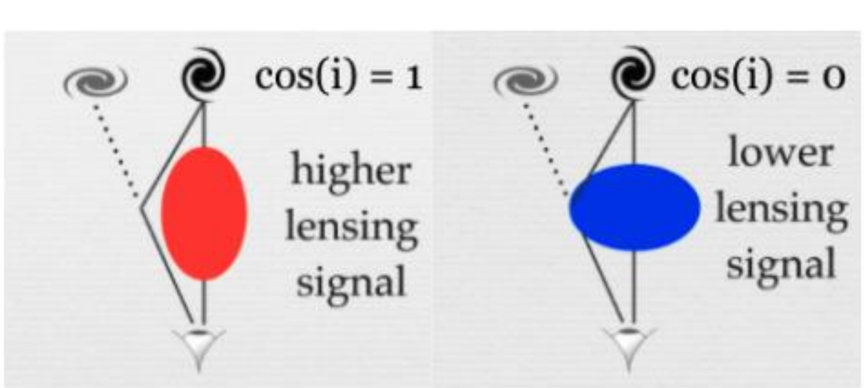


Figure 2: For an ellipsoidal cluster the lensing signal and richness count is boosted when it's major axis is aligned with the line of sight. The cosine of the angle between the major axis and the line of sight is denoted $\cos(i)$.

Cluster triaxiality refers to the intrinsically elliptical shape of galaxy clusters. Triaxiality is one of the most prominent systematic biases in the DES Year 1 cluster lensing study. Significant at a 2% level, it is among the most dominant selection effect systematics. **Clusters with their major axes along the line of sight have both their weak lensing signal and observed richness boosted, affecting the MOR in a twofold manner.**

This project aims to use the Buzzard simulation to probe the nature of triaxiliaty bias and to resolve the bias with a forward modeling template for current and near-future weak lensing surveys.

MODELING TRIAXIALITY BIAS

Shape and Ellipticity Bias

Using the eigenvalues and eigenvectors of the quadrupole moment to the determine the shape and orientation of redMaPPer-selected clusters, we compare them to randomly selected ones to determine whether redMaPPer biases the shape or orientation. **We find that redMaPPer biases the orientations towards high cos(i) but does not significantly bias the shape (Fig. 3 & 4).**

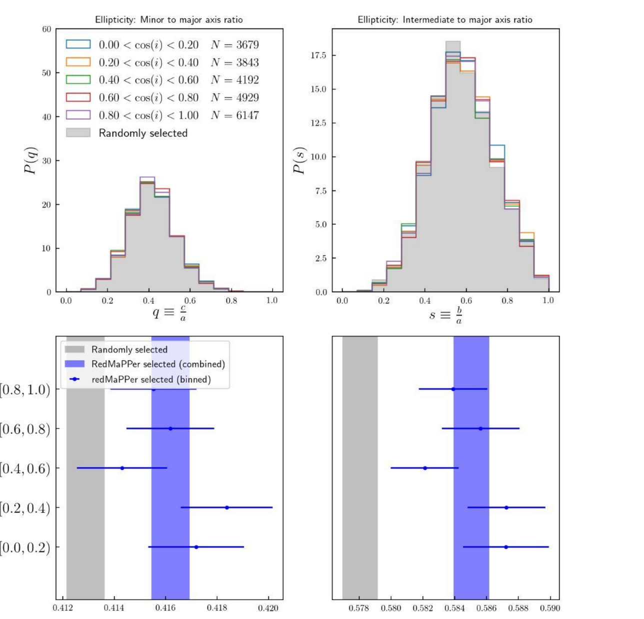


Figure 3: *top*: Axis ratio distributions for redMaPPer matched clusters binned by orientation versus randomly selected halos in the BCC catalog. *bottom*: Mean axis ratios with errors produced by jackknife resampling. No statistically significant shift in q is found between redMaPPer matched and randomly selected halos, and a marginally significant shift in s. In either cases no statistically significant difference is found in the mean ellipticities across different orientation bins.

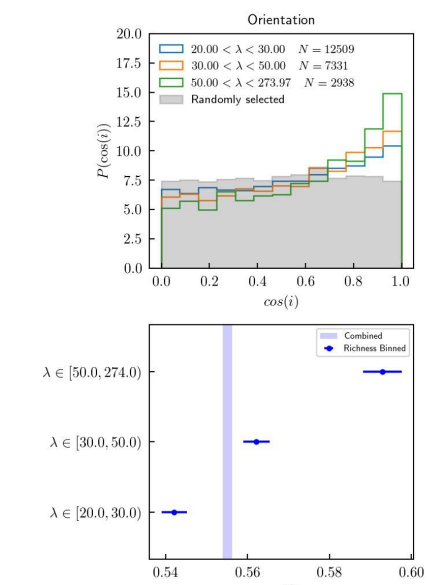


Figure 4: *top*: Distribution of $\cos(i)$ of redMaPPer matched versus randomly selected halos. *bottom*: Mean distribution of redMaPPer selected clusters show a significant boosting in mean $\cos(i)$ compared to randomly selected halos (not shown). As a sanity check we find the mean $\cos(i)$ of randomly selected halos is consistent with 0.50. The figure also displays boosting of $\cos(i)$ with increasing richness, which can be explained by the boosting of richness of less massive halos into larger richness bins as a result of orientation bias. Errors are produced with jackknife resampling.

Modeling the richness-mass bias

As previous studies we model the observed richness-mass (λ-M) of clusters as a log-linear relation:

$$\mu(\ln\lambda)=\log(A)+B\times(\ln M-14\ln(10))$$

Binned by different orientation bins we find that there is a significant shift in log(A) (Fig. 5) while the slope and scatter remain relatively fixed, the amplitude of the richness as a function of mass, congruent with the hypothesis that triaxiality boosts the richnesses of clusters.

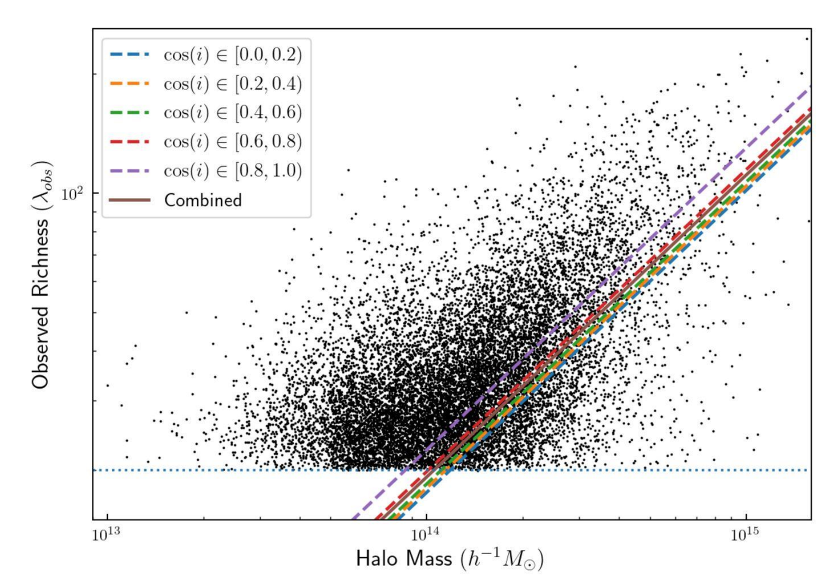


Figure 5: Richness-mass scatter plot and fit for different orientation bins. The catalogs cuts off clusters with richness $\lambda < 20$, and for accurate halo-cluster matching halos are applied a mass cut of $M_{200b} > 10^{13}$ $M_\odot$. Assuming a linear relationship in $\log(\lambda)$-$\log(M)$ the trendlines affirm the hypothesis that triaxiality biases the richness-mass relationship as a boosting in the richness for a given mass. The trendlines are pulled to the right of the scatter plot as a correction to the richness cutoff that eliminates many potential scatter points below the trendlines.

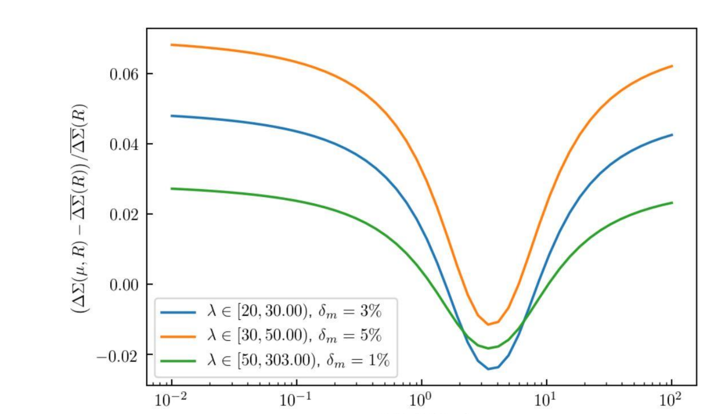


Figure 6: Fractional difference in lensing profiles for redMaPPer-selected clusters stacked in bins of richness. The mass bias for each bin is indicated in the legend. This has been calculated through propagating the errors of the lensing profile onto the mass model parameter using a Fisher forecast.

Total mass bias

We arrive at the triaxiality-corrected average surface density in a richness-binned stack of clusters--a direct observable of weak lensing surveys, by integrating the bias correction for the richness-mass and the surface density of lensing profiles binned by orientation.

The fractional difference of stacked profiles for redMaPPer-selected clusters including and without triaxiality-bais correction is plotted above in Figure 8. We use a Fisher forecast to predict the total mass bias of clusters before accounting for this correction.

$$\delta M_{\rm total} = \sum_{M,z} P(M,z|\lambda)\left[\sum_j (F^{-1})_{ij}\left(\boxed{(\delta\langle\Delta\Sigma\rangle)}\mathrm{Cov}(\langle\Delta\Sigma\rangle)^{-1}\frac{\partial\Delta\Sigma}{\partial p_j}\right)\right]$$

We find an overestimation of cluster weak lensing mass by 1-5%, highest at mid-high richness ranges (Fig. 6). This is consistent with the findings from the recent DES Y1 Cluster Cosmology study that showed that triaxiality and projection effects could resolve the tension between DES and other cosmological probes at richness > 30 but does not account for the bias in lower richnesses.

CORRELATION WITH OTHER EFFECTS

Miscentering

We quantify the degree of miscentering in Buzzard in two ways (Fig. 9): One is by measuring the fractional difference in richness found by centering redMaPPer on the top and second central galaxy candidate, as was done with DES Y1 data. Second is by comparing the fractional difference in richness between the full redMaPPer run in Buzzard and a *halorun* that artificially centers redMaPPer on the correct halo centers.

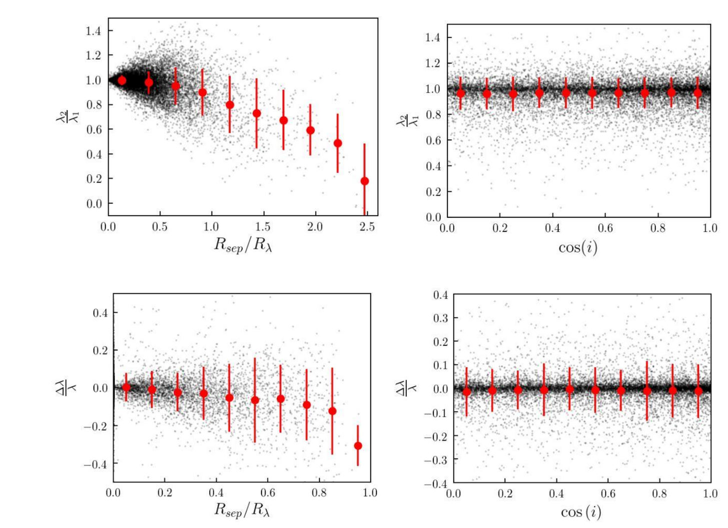
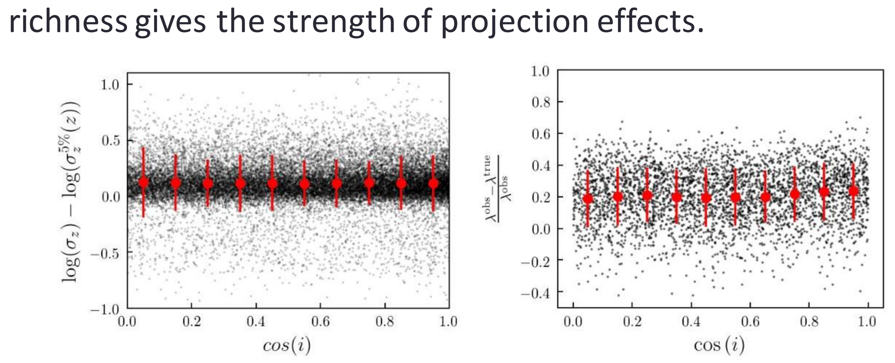


Figure 7: **(Left panels)** Miscentering bias vs. miscentering separation distance. Both miscentering bias metrics $\frac{\lambda_2}{\lambda_1}$ and the fractional richness difference between *halorun* and *fullrun* $\frac{\Delta\lambda}{\lambda}$ reproduce the trends from DES Y1 of decreasing ratio and increasing dispersion with separation distance. This result robustly validates that the miscentering bias in Buzzard behaves in the same way as real data. **(Right panels)** Having validated the miscentering bias metrics $\frac{\lambda_2}{\lambda_1}$ and $\frac{\Delta\lambda}{\lambda}$, we find that they are completely uncorrelated with halo orientation. This result shows that miscentering and triaxiality should be treated as separate systematics.

In both cases we successfully reproduced the miscentering bias of richness, and in both cases, the degree of miscentering was uncorrelated with the degree of triaxiality bias (Fig 7).

Projection

Projection effects refer to the bias in observed richness when clusters are in the line of sight of projected structure such as filaments, other clusters or isolated galaxies. The strength of projection effects in observable data can be characterized by the projection kernel **σ_z(z)**, the redshift range from the cluster at which projection effects can take place. The fraction difference between the observed and true richness gives the strength of projection effects.



(a) Correlation of $\sigma_z^{\rm proxy}$ with halo orientation. (b) Correlation of $\frac{\Delta\lambda}{\lambda}$ with halo orientation.

Figure 8: Correlation of strength of projection effects with halo orientation in the Buzzard projection mock catalog. Two metrics are measured in the catalog—$\sigma_z^{\rm proxy}$, the depth of projection effects and $\frac{\Delta\lambda}{\lambda}$, the fractional difference between observed and true richness assigned by the full expression $P(\lambda^{\rm obs}|\lambda^{\rm true}, z)$ that convolves richness biases from background noise, correlated large scale structure and percolation effects. Using $\sigma_z^{\rm proxy}$ or the fractional richness difference we test for a null correlation between the two systematics.

In both cases, projection bias was uncorrelated with the degree of triaxiality bias (Fig 8).

CONCLUSIONS

This work uses the extragalactic catalog of the Buzzard N-body simulation with redMaPPer identified clusters to quantify triaxiality bias and test its correlations with other leading known systematics. The main findings of this work are:

- Finds no change in the prolateness of halo distribution for redMaPPer selected clusters and a significant change in the cos(I) distribution of selected clusters.
- Quantifies the change in richness-mass amplitude and cluster surface density profiles as a function of orientation.
- Tests for null correlation between triaxiality and two other leading systematics in DES Y1 cluster cosmology---miscentering and projection, and offers explanations or follow-up studies for this result.
- Quantifies the DES observable of richness-stacked redMaPPer cluster lensing profiles to predict an upward mass bias of 1-5% after correcting for triaxiality.

This work may be useful for the reduction of triaxiality bias in upcoming cluster weak lensing surveys.